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Multi-Disciplinary Coupling Effects for Integrated Design of Propulsion Systems

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MULTIDISCIPLINARY COUPLING EFFECTS FOR INTEGRATED DESIGN OF PROPULSION SYSTEMS

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SUMMARY

Effective computational simulation procedures are described for modeling the inherent multidisciplinary interactions which govern the accurate response of propulsion systems. Results are presented for propulsion system responses including multidisciplinary coupling effects using (1) coupled multidiscipline thermal/structural/acoustic tailoring, (2) an integrated system of multidisciplinary simulators, (3) coupled material-behavior/fabrication process tailoring, (4) sensitivities using a probabilistic simulator, and (5) coupled materials/structures/fracture/probabilistic behavior simulator. The results demonstrate that superior designs can be achieved if the analysis/tailoring methods account for the multidisciplinary coupling effects. The coupling across disciplines can be used to develop an integrated coupled multidiscipline numerical propulsion system simulator.

1. INTRODUCTION

Propulsion phenomena are inherently multidisciplinary, i.e., the true system response is the coupled effect of all the participating disciplines and the aggregate of the responses and interactions of the system components. Present analyses tend to focus on single-discipline response within a local region, e.g., a single component. Suitable approximations are then used to extend these analyses to subsystems and systems.

The performance and reliability of propulsion systems depend on the interaction of their subsystems which, in turn, depend on the interaction of their respective components (ref. 1). The performance of a specific component depends on the coupled effects of the system multidisciplinary interaction on the component response (fig. 1). Further, the integrated system response depends on the progressive and interacting influence of the coupled service loads/environments at all levels from subcomponent, to component, to subsystem, to system. Interaction phenomena of interest include flutter, rotor instability, fatigue, flow separation, nonuniform combustion, blade containment, and noise suppression. The determination of aerothermodynamic system performance has traditionally relied on prototype tests whereas structural reliability has been determined from field data.

The analysis of propulsion phenomena involves a combination of disciplines including fluid mechanics, thermal sciences, structural mechanics, material sciences, acoustics, electromagnetics, and control theory. The degree of resolution within a specific discipline is determined by the magnitude of local effects and the extent of their region of influence. To credibly quantify local effects, coupled multidisciplinary methods are required. Therefore, the objective of this paper is to present results demonstrating the

multidisciplinary interaction in propulsion systems using formal coupled multidisciplinary methods. Appropriate references are cited for detailed descriptions of methods and computer codes.

2. MULTIDISCIPLINARY COUPLING METHODS

Recent advances in the computational simulation of fluid, thermal, structural, material, acoustic, and electromagnetic response and computational automatic controls provide an opportunity to consider the development of coupled multidisciplinary computational simulation methods. The coupling methods provide the formalism to generate the terms shown in the array in table 1, as will be described extensively in section 2.7. Single discipline simulations produce the diagonal sub arrays while coupled multidisciplines produce the off-diagonal terms. Many computational methods/codes are available for solving unidisciplinary problems as was mentioned previously. In this section, we describe how existing computational methods/codes are used to simulate the multidiscipline coupled response of various propulsion components which are subjected to a multitude of simultaneous loads.

2.1 Coupled Multidiscipline Tailoring

A coupled multidisciplinary composite-materials/hygral/thermal/structural/acoustic/electromagnetic analysis/tailoring code, CSTEM (ref. 2) can be used to tailor the single or multidiscipline responses of propulsion structures. CSTEM was used for tailoring a multilayered composite fan blade subjected to multidiscipline influences (fig. 2). The composite materials behavior was analyzed using an integrated composite analyzer (ref. 3) starting from the lowest composite scale (fiber/matrix constituents) to higher scales (ply, laminate) using composite micromechanics and laminate theory (fig. 3). The laminates material behavior is used to determine global structural response using finite element methods. The global structural response is then decomposed to the lower composite scales using laminate theory and composite micromechanics. A nonlinear material characterization model (fig. 4) is used at the constituents scale to account for the effects of service environments.

The laminate configurations of the initial and tailored fan blade designs are shown in figure 5. The middle part of figure 5 shows three cases of tailored laminate configurations as a result of unidisciplinary tailoring for weight, maximum temperature difference, and cost, separately. Two cases, shown at the bottom of figure 5, are for the coupled multidisciplines, namely: coupled composite-mechanics/heat-transfer/vibrations and coupled composite-mechanics/heat-transfer/vibrations/acoustic responses. The effect of heat transfer loads is carried through the temperature profiles at all composite scales that, in turn, affect the materials behavior and thus the vibration response of the blade. The later case includes the effects of temperature on the blade's acoustic characteristics. The acoustic response includes all the interaction effects, namely: (1) heat-transfer loads, (2) thermal, mechanical, and acoustic resistance of the material, and (3) blade vibration characteristics. The CSTEM code provides a wealth of information such as the laminate configurations required for tailored responses of different disciplines, which can sometimes be opposite to each other, as is evident from figure 5. The off-diagonal terms in table 1 can be developed by evaluating the other disciplines at the optimum design.

2.2 Multi-Objective Optimization

An example is presented to demonstrate the capability to optimize the structural response resulting from several disciplines interacting simultaneously. Figure 6 (ref. 4) shows a candidate composite structure optimized for single and multi-objective functions. The structure is made of graphite/epoxy composite with

a fiber volume ratio of 0.5. The structure is first optimized for displacement amplitude, weight, and cost separately. The structure is then optimized for the displacement amplitude, weight, and cost simultaneously. The decision variables in all cases are ply orientations and stiffnesses.

The results showing the initial and optimum objective values are included in figure 6. The initial values of all three objective functions are shown as 100 percent. The percent change in each of the three objective functions is then shown for three different optimization runs, each run optimizing one objective function separately. The right most bars in figure 6 show the optimum objective functions when all three objective functions are optimized simultaneously. The best design within the specified constraints is obtained when the multi-objective function is used.

2.3 Integrated System of Multidisciplinary Analysis

A nonlinear materials behavior simulator (ref. 3) and a finite element code (ref. 5), and the coupled multidiscipline code CSTEM (ref. 2) were integrated for simulating the fatigue behavior of a multilayered hot and wet composite panel acoustically excited by an adjacent vibrating hot panel (fig. 7), typical of aircraft components.

Figure 8 shows the acoustic fatigue life results for three different laminate configurations of the composite panel. The results are based on a coupled composite-material/hygral/thermal/structural/acoustic simulation. Figure 8 illustrates that the fatigue life of the acoustically excited panel can be increased substantially by placing off-axis plies on the outer surface of the laminate. The important point is that the coupled multidisciplinary response of composite structures can be computed to yield superior designs, with no unexpected failures when operating in real-life service environments since the analysis captures the various multidisciplinary coupling effects (interactions).

2.4 Coupled Material-Behavior/Fabrication-Process Tailoring

The fabrication process of a composite laminate can be tailored for desired optimum single discipline or multidiscipline objectives using a Metal Matrix Laminate Tailoring code, MMLT (fig. 9, ref. 6).

The results in figure 10 show the laminate characteristics (extensional stiffness, compressive load capacity, bending stiffness, and bending load capacity) that can be attained for individual stiffness or load maxima as well as for concurrent stiffness/load maxima.

2.5 Sensitivities Using Probabilistic Methods

The sensitivities of the effective stress for a second stage turbine blade at two different blade locations were assessed via a probabilistic structural behavior simulation (ref. 7). Figure 11 shows the blade model and probabilistic distributions of the blade geometry, material, and mechanical/thermal loads.

The cumulative probability for the effective stress at two different blade locations is included in figure 11. The importance (sensitivity) factors for five dominant variables were found to be different and with different importance ranking at different blade locations. The importance factors in figure 11 are listed in decreasing order of importance of their effect on the effective stress. These are the off-diagonal terms in the array, table 1. The deterministic structural analysis will not provide the sensitivity information

which can be crucial in designing structures effectively. The important point is the material/structural behavior is modeled based on real-life uncertainties in all the design variables.

2.6 Coupled Materials/Structures/Fracture/Probabilistic Behavior Simulator

A progressively more inclusive integration of the various discipline-specific simulators is made possible with the existing infrastructure at NASA Lewis Research Center. An example of probabilistic crack initiation and growth for a rotor blade is shown in figure 12.

The results of the coupled materials/structures/fracture/probabilistic behavior of the rotor blade, including interactions due to uncertainties in various design variables at their lowest levels (called primitive variables) are included in figure 12. The direction of the fracture path is determined, not by a specific analysis, but by the above-mentioned coupled effects.

The success in applying coupled materials/structures/fracture/probabilistic simulation for structural components will enable utilization of multiple levels of parallelism in large scale structures. It will then be possible to solve for large number of structural response variables. A high degree of cost effectiveness in risk/reliability assessment will be achievable. For better accuracy, three-dimensional finer meshes can be modeled.

2.7 Multidiscipline Sequential Optimization

An integrated simulator for propulsion systems will entail a very large number of coupled (interrelated) variables. In addition to coupled multidiscipline simulators discussed above, innovative approaches are needed to reduce the dimensionality of the system description while still retaining the essential system behavior. The viable approaches include sequential iterations between disciplines, specially-derived system matrices, and coupling at the fundamental equation level. The coupling across disciplines in a concurrent multidisciplinary formulation can be represented by coupling relations. The coefficients (elements) in these relations define the coupling of a specific variable from one discipline with respective variables from interacting disciplines (table 1).

Perturbation of the variables in the coupling relations provides a measure of the sensitivity of the interacting disciplines to this perturbation. An up-front quantification of this relationship sensitivity enhances the computational simulation in several respects: (1) scoping the degree of coupling, (2) identifying the interacting disciplines, (3) resolving time/space scales, (4) selecting time/space scale for loosely coupled interacting discipline intervention during the solution processes, (5) deciding on a solution strategy, and (6) imposing convergence criteria.

Four different methods are being pursued for defining and deriving sensitivity relations. These are: (1) heuristic—based on available traditional single discipline approaches and expert opinion, (2) multidiscipline sequential optimization—based on determining the primitive variables for optimum response within a single discipline, determining the response for optimized primitive variables for all coupling disciplines, and repeating the process for each discipline of interest, (3) probabilistic evaluation—by determining the sensitivities of multidisciplinary response to interrelated primitive variables, and (4) fundamental coupled formulation—based on mixed-field finite elements coupling the primitive equations. The results for the multidiscipline coupling of the propulsion component responses using these techniques are being acquired. These results will then be processed to compute the coupling coefficients of the specialty multidisciplinary matrices.

3. NUMERICAL PROPULSION SYSTEM SIMULATOR (NPSS)

The existing infrastructure can be used to develop an integrated interactive multidisciplinary computational simulator. Such a system is under development called Numerical Propulsion System Simulator (NPSS) shown schematically in figure 13 (ref. 1). NPSS will allow comprehensive simulation of entire propulsion system concepts and designs before committing to hardware. It will include recent multidisciplinary computational tailoring models to allow the selection of better, cheaper, and faster propulsion designs for desired performance. In addition, reliability-based propulsion design will be possible with the recent progress in probabilistic methods that account for uncertainties at various levels of propulsion systems. This will greatly reduce (1) the design space for new systems, (2) our dependence on extensive hardware testing for proof-of-concept and system integration demonstrations, and (3) the need of testing required in the development process.

The NPSS will enable the incorporation of new methodologies such as concurrent engineering into the propulsion design process. NPSS will provide the capability to conduct credible, multidisciplinary analyses/tailoring of new propulsion concepts and designs more quickly and less costly.

In essence, the NPSS will include all the key enabling technologies for integrated multidisciplinary analysis and tailoring of propulsion systems. The existing infrastructure will be used while maintaining flexibility to utilize emerging massively parallel computer hardware platforms. The simulator architecture as shown in figure 14 consists of the simulator executive controlling the various simulation codes, libraries, data management facilities, controls, graphic visualization facilities, information systems, and expert systems. A schematic of the multidiscipline coupling for propulsion components in figure 15 shows (1) the interactions between the aero/heat-transfer effects and the mechanical clearance of the structures, (2) the interactions between the aero system response and the inlet fan map, (3) the coupling of structures system response and fan loads, and (4) the coupled aero blade load and blade tip clearance effect.

4. CONCLUDING REMARKS

Computational simulation is a natural and cost-effective method to evaluate multidiscipline coupling. Concurrent development of multidisciplinary computer codes has provided the infrastructure to computationally simulate multidiscipline coupling. The coupling across disciplines in a concurrent multidisciplinary formulation can be represented by coupling relations. The coefficients in these coupling relations can be determined by various techniques including sequential optimization, probabilistic approaches, and coupled fundamental formulations. The results show that coupling effects can be modeled using existing codes. The coupling methods combined with other suitable infrastructure are being used for developing a numerical propulsion system simulator for designing/analyzing propulsion systems.

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Table 1 - Coupled Multi-discipline Representation for Aerospace Propulsion Systems

$$
\underbrace{\begin{Bmatrix} \{A\} \\ \{T\} \\ \{S\} \\ \{M\} \\ \{F\} \\ \{P\} \\ \{C\} \end{Bmatrix}}_{\substack{\text{System}\\ \text{Response Variables}}}
=
\underbrace{\begin{bmatrix}
[A^{A}_{A}] & [T^{T}_{A}] & [S^{S}_{A}] & [M^{M}_{A}] & [F^{F}_{A}] & [P^{P}_{A}] & [C^{C}_{A}] \\
[A^{A}_{T}] & [T^{T}_{T}] & [S^{S}_{T}] & [M^{M}_{T}] & [F^{F}_{T}] & [P^{P}_{T}] & [C^{C}_{T}] \\
[A^{A}_{S}] & [T^{T}_{S}] & [S^{S}_{S}] & [M^{M}_{S}] & [F^{F}_{S}] & [P^{P}_{S}] & [C^{C}_{S}] \\
[A^{A}_{M}] & [T^{T}_{M}] & [S^{S}_{M}] & [M^{M}_{M}] & [F^{F}_{M}] & [P^{P}_{M}] & [C^{C}_{M}] \\
[A^{A}_{F}] & [T^{T}_{F}] & [S^{S}_{F}] & [M^{M}_{F}] & [F^{F}_{F}] & [P^{P}_{F}] & [C^{C}_{F}] \\
[A^{A}_{P}] & [T^{T}_{P}] & [S^{S}_{P}] & [M^{M}_{P}] & [F^{F}_{P}] & [P^{P}_{P}] & [C^{C}_{P}] \\
[A^{A}_{C}] & [T^{T}_{C}] & [S^{S}_{C}] & [M^{M}_{C}] & [F^{F}_{C}] & [P^{P}_{C}] & [C^{C}_{C}]
\end{bmatrix}}_{\substack{\text{System Definition/Characteristics}\\ \text{and Coupling Relationships}}}
\underbrace{\begin{Bmatrix} \{A\} \\ \{T\} \\ \{S\} \\ \{M\} \\ \{F\} \\ \{P\} \\ \{C\} \end{Bmatrix}}_{\substack{\text{System}\\ \text{Development}\\ \text{\& Service}\\ \text{Parameters}}}
$$

A Aero
T Thermal
S Structural
M Material
F Fabrication
P Performance
C Cost

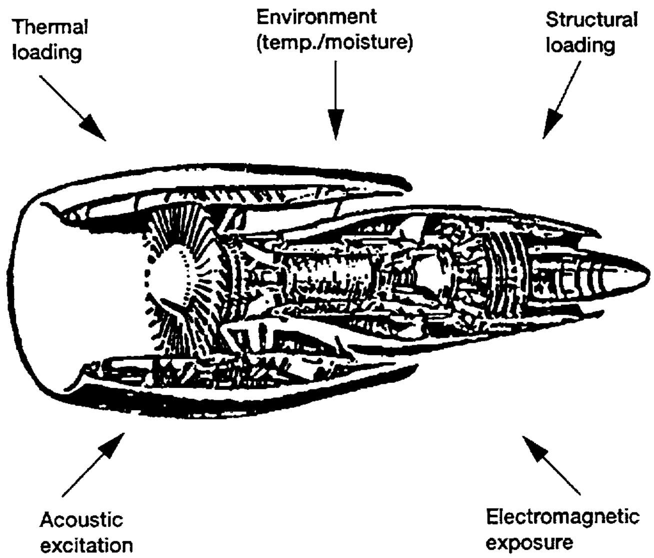
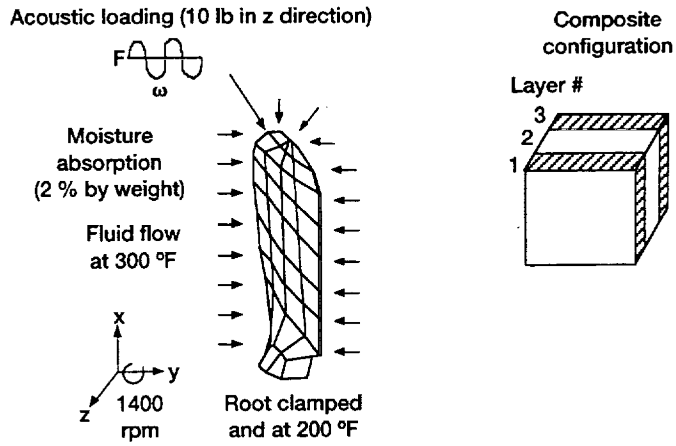


Figure 1.—Engine components under service-environment loadings.



Initial design values

Layer #	Material	Thickness (fraction)	Orientation w.r.t. x-axis (deg.)
1	T300/IMHS	0.25	30
2	Titanium	0.5	0
3	T300/MHS	0.25	30

Figure 2.—Multi-material multi-layered composite fan blade: Initial design under multidisciplinary loadings.

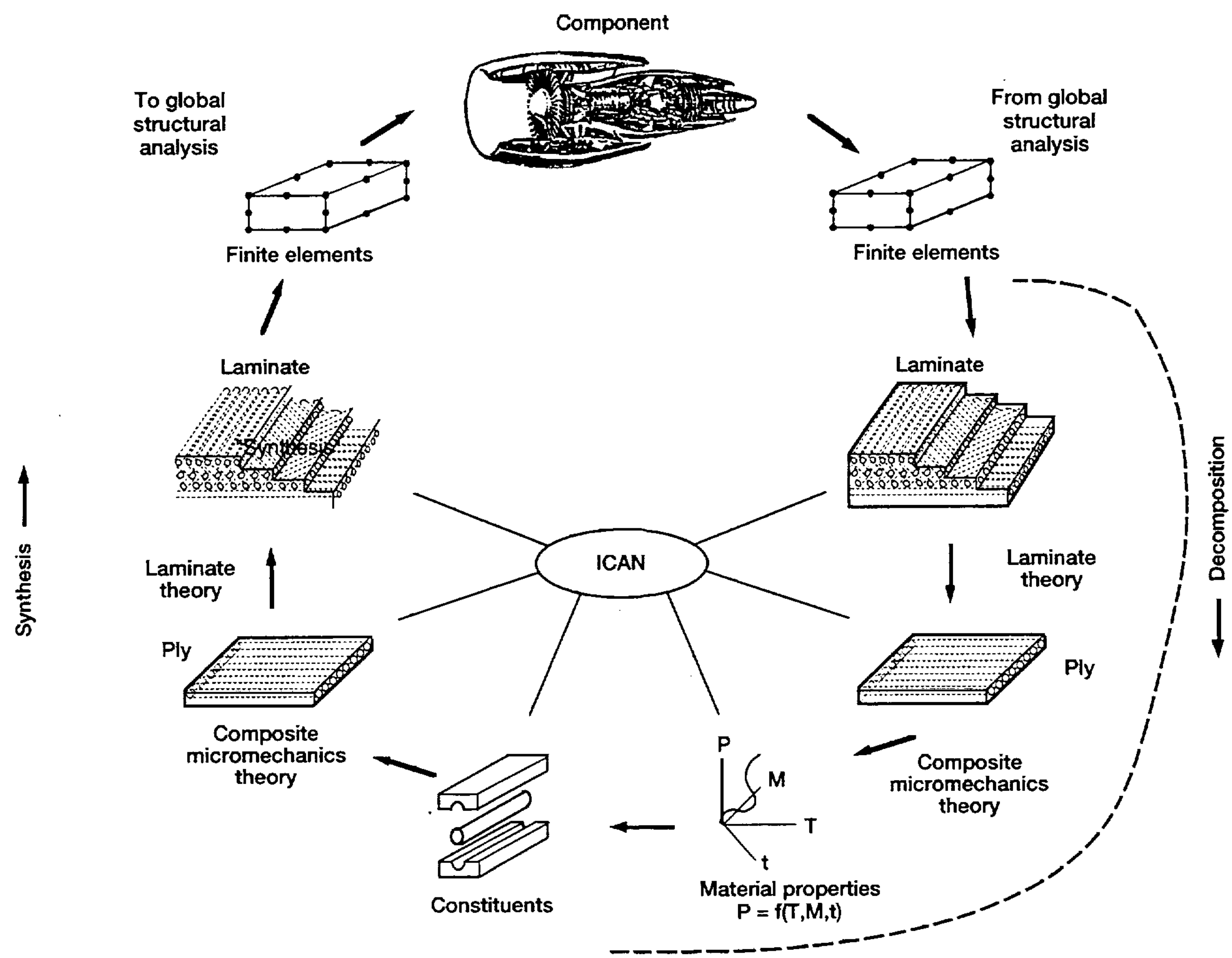
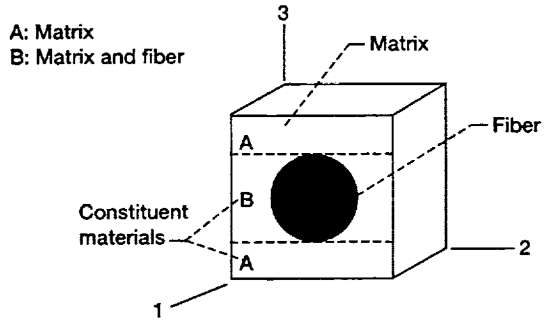


Figure 3.—Integrated composite analysis (ICAN).



$$\frac{P_M}{P_{M0}} = \left[\frac{T_{GW} - T}{T_{GD} - T_0}\right]^{1/2}$$

$$T_{GW} = (0.005\, M^2 - 0.1\, M + 1)\, T_{GD}$$

P_M = Matrix property at current temp., T
P_{M0} = Matrix property at reference temp., T_0
T_{GW} = Wet glass transsition temp.
T_{GD} = Dry glass transsition temp.
M = Moisture % by weight.

Figure 4.—Regions of constituent materials and nonlinear material characterization model.

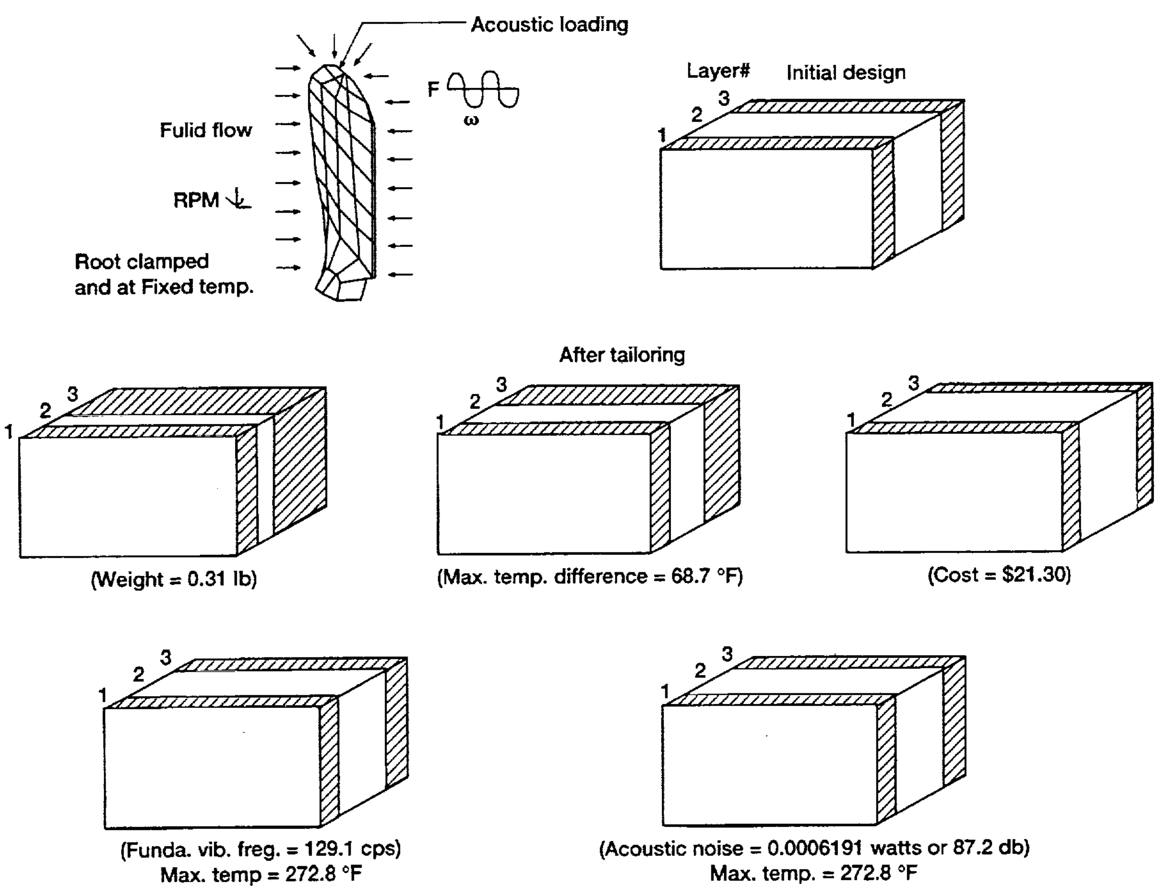


Figure 5.—Multi-material multi-layered composite fan blade: Tailored designs under multi-disciplinary loadings.

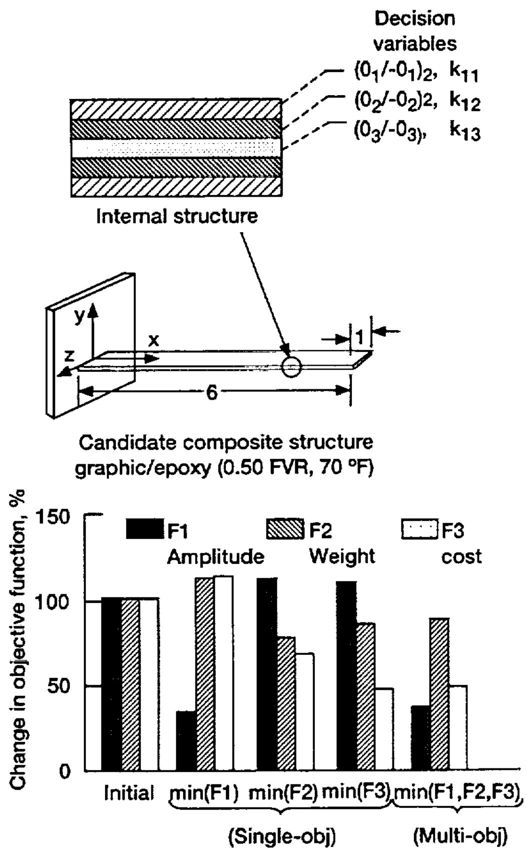


Figure 6.—Multi-objective optimization.

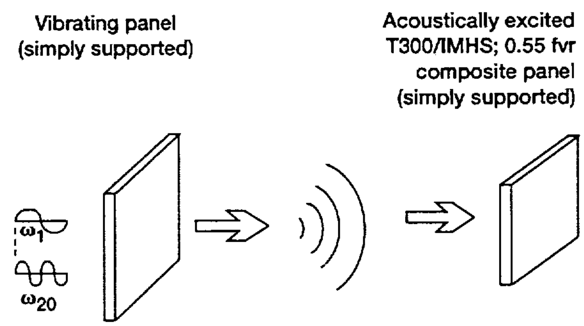


Figure 7.—Acoustically exicted compostie panel.

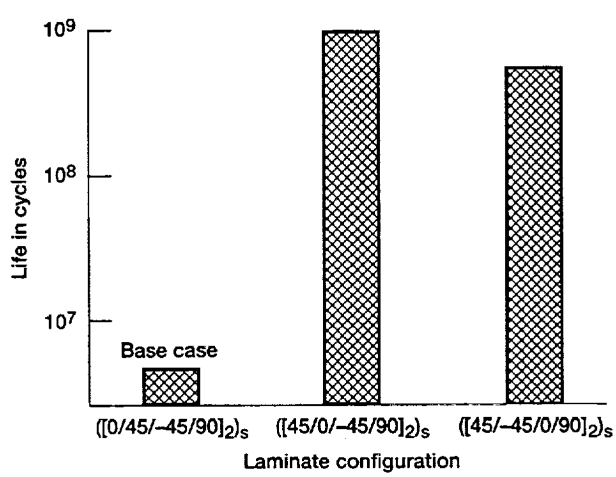


Figure 8.—Coupled composite-material/hygral/thermal/structural/ acoustic simulation: effect of laminate configuration.

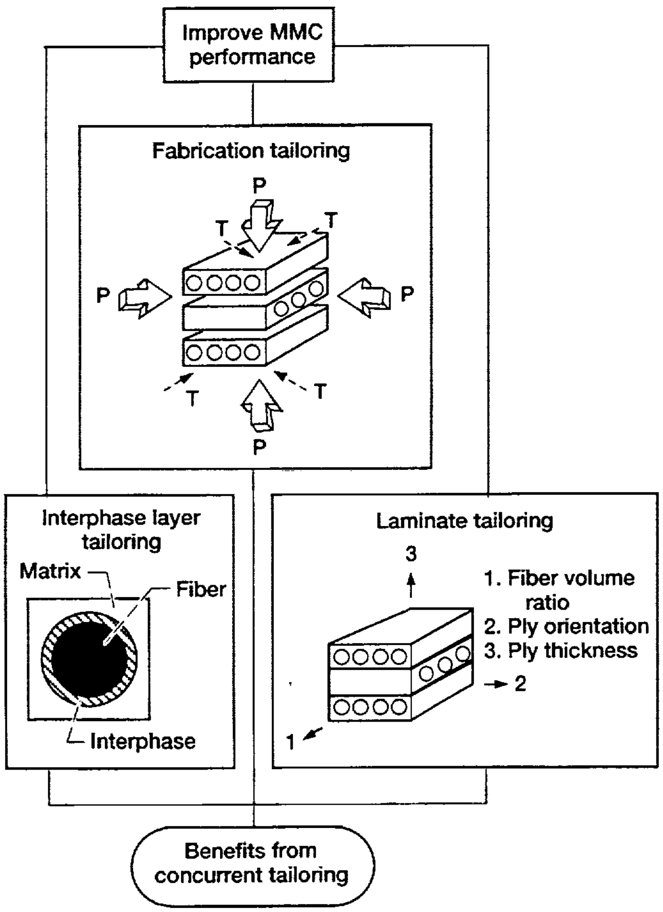


Figure 9.—Metal matrix laminate tailoring.

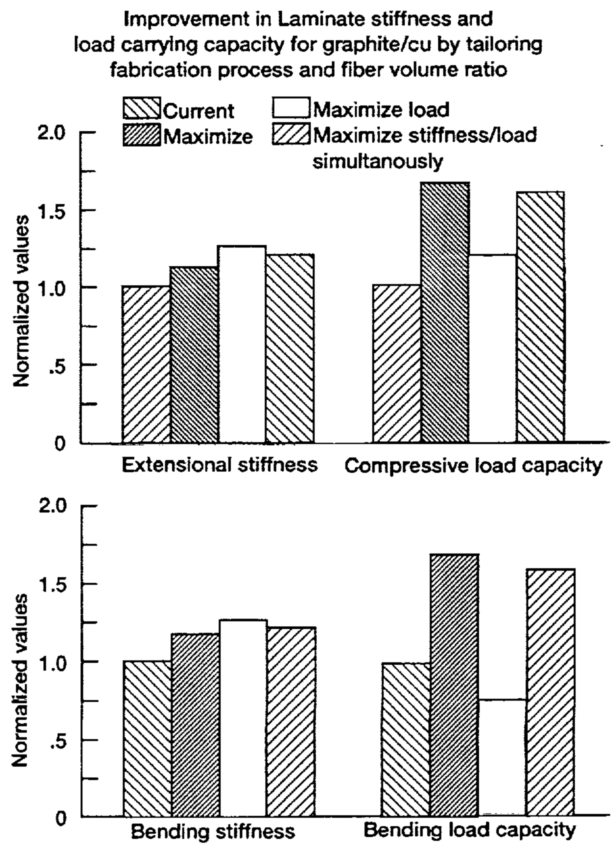


Figure 10.—Metal matrix laminate tailoring to improve load carrying capacity.

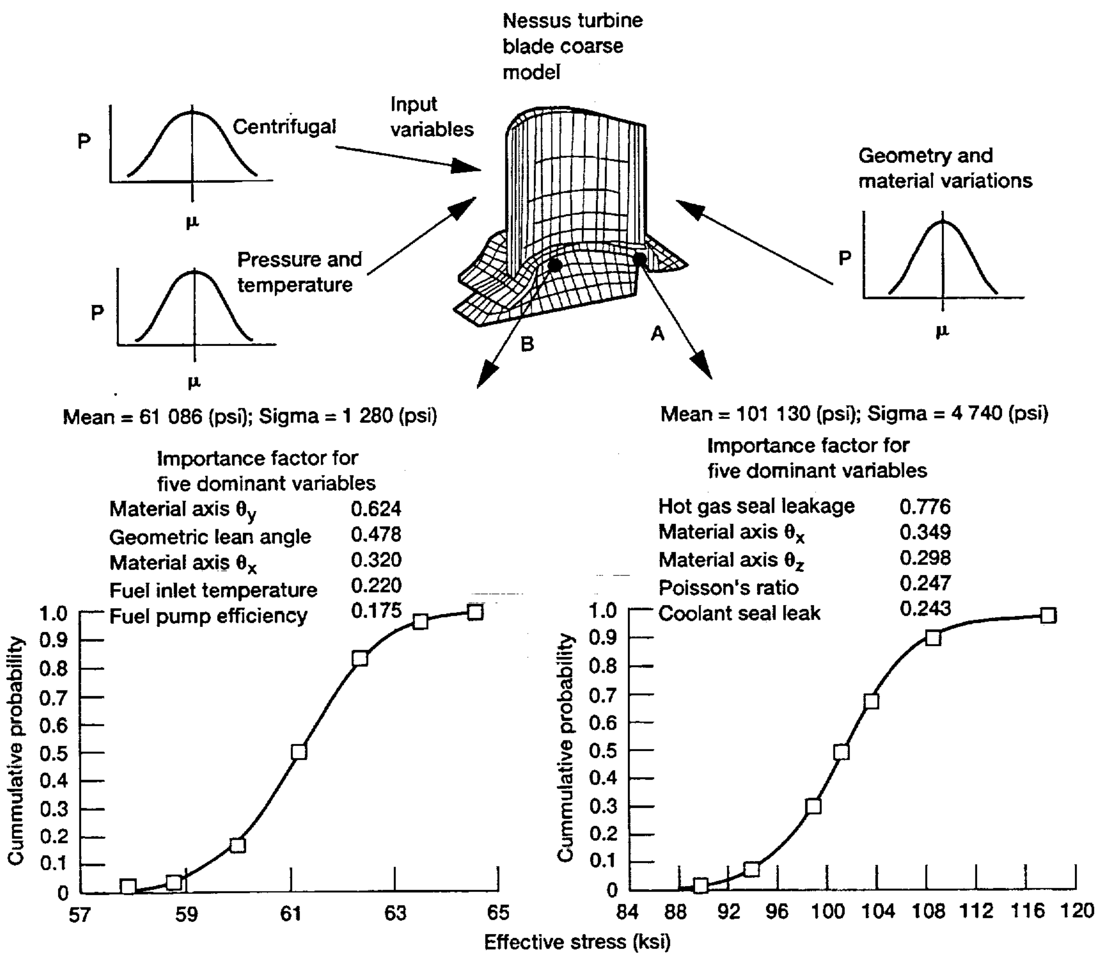


Figure 11.—Probabilistic component stress and sensitivities analyses.

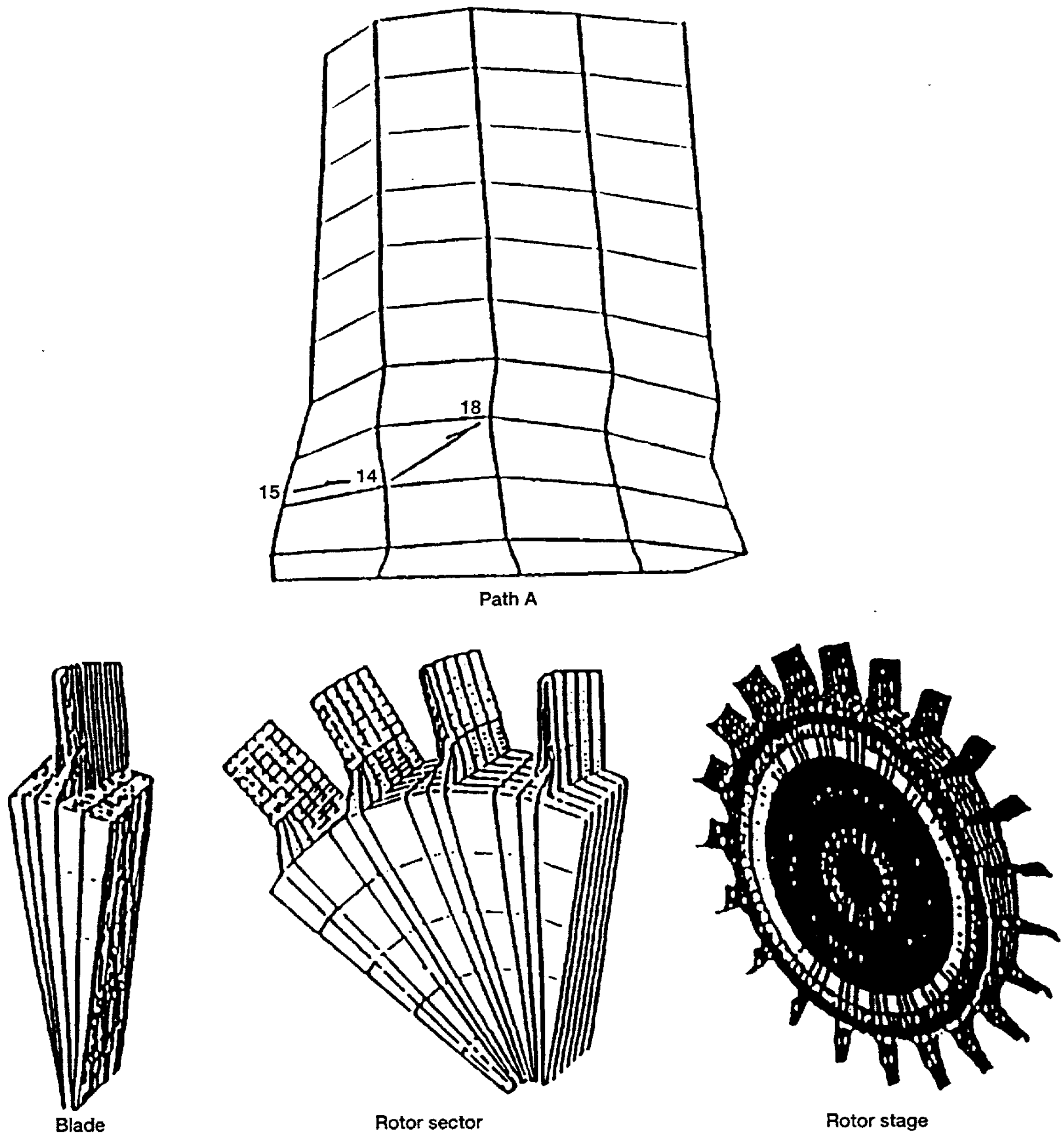


Figure 12.—Fracture path of a rotor blade.

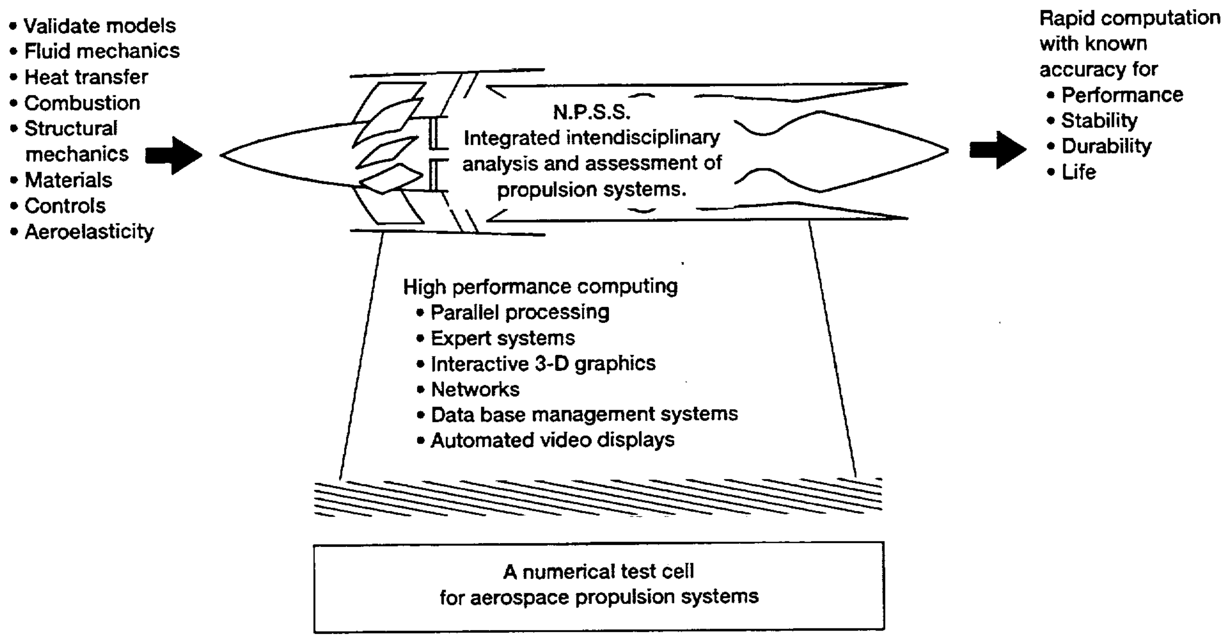


Figure 13.—Numerical test cell simulator.

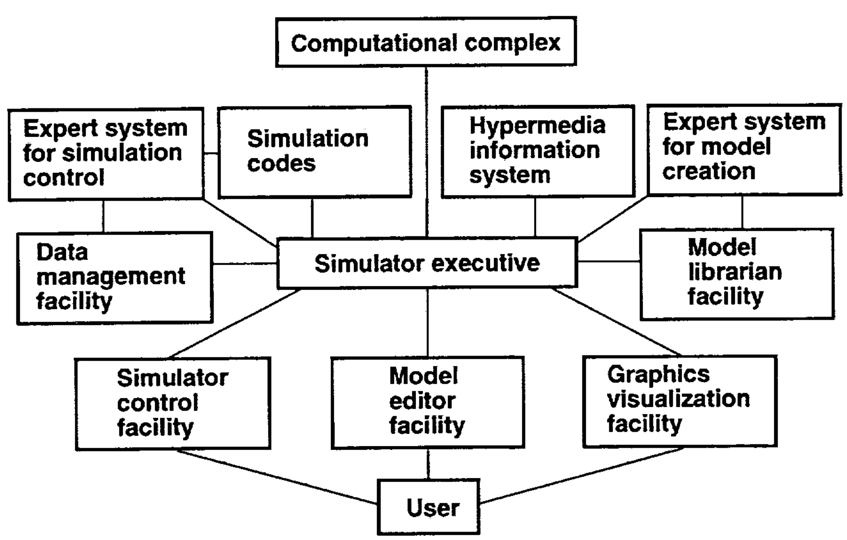


Figure 14.—Simulator architecture.

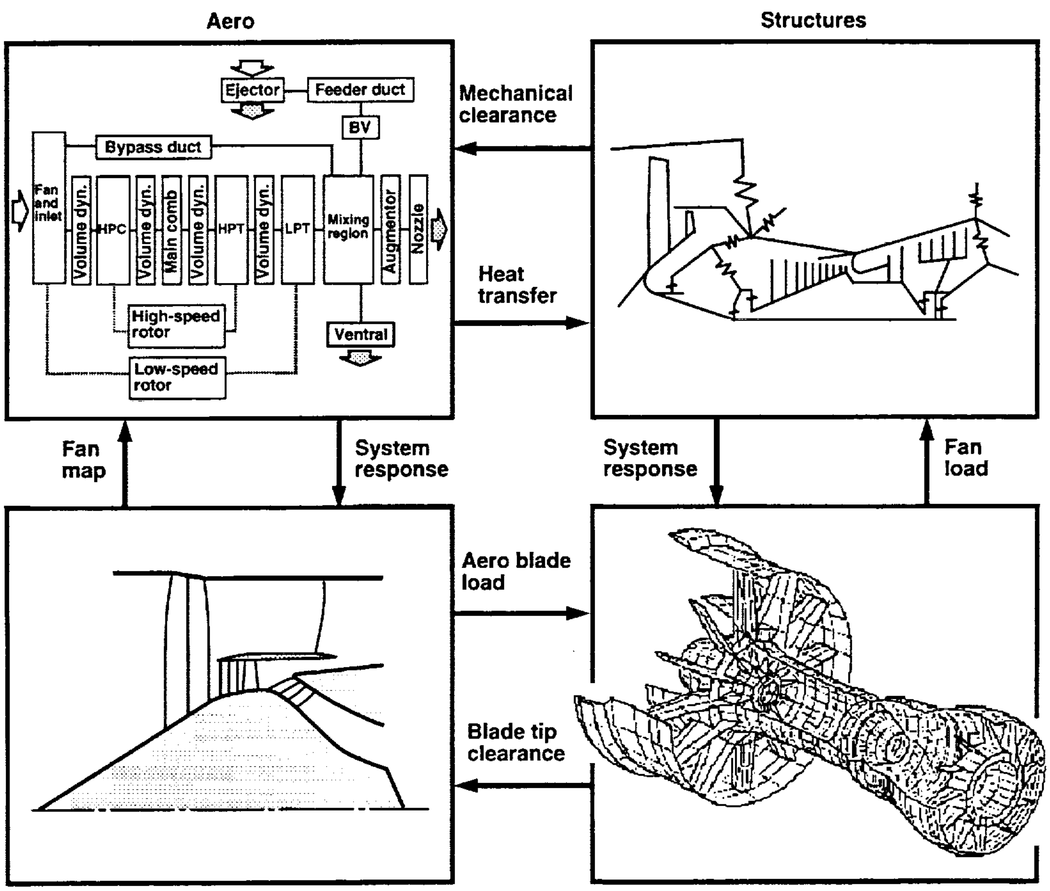


Figure 15.—Simulator models.

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13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS
Acoustics; Composites; Computational simulation; Environments; Fabrication; Fluid flow; Fracture; Heat transfer; Integrated simulators; Material behavior; Metal matrix composites; Multi-discipline coupling; Multi-objective optimization, Polymer matrix composites; Probabilistic behavior; Propulsion system, Sensitivities; Structural response, Tailoring; Thermal analysis; Vibration

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